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Ecological effect of the plantation of *Sabina vulgaris* in the Mu Us Sandy Land, China

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Abstract: Vegetation restoration through artificial plantation is an effective method to combat desertification, especially in arid and semi-arid areas. This study aimed to explore the ecological effect of the plantation of *Sabina vulgaris* on soil physical and chemical properties on the southeastern fringe of the Mu Us Sandy Land, China. We collected soil samples from five depth layers (0–20, 20–40, 40–60, 60–80, and 80–100 cm) in the *S. vulgaris* plantation plots across four plantation ages (4, 7, 10, and 16 years) in November 2019, and assessed soil physical (soil bulk density, soil porosity, and soil particle size) and chemical (soil organic carbon (SOC), total nitrogen (TN), available nitrogen (AN), available phosphorus (AP), available potassium (AK), cation-exchange capacity (CEC), salinity, pH, and C/N ratio) properties. The results indicated that the soil predominantly consisted of sand particles (94.27%–99.67%), with the remainder being silt and clay. As plantation age increased, silt and very fine sand contents progressively rose. After 16 years of planting, there was a marked reduction in the mean soil particle size. The initial soil fertility was low and declined from 4 to 10 years of planting before witnessing an improvement. Significant positive correlations were observed for the clay, silt, and very fine sand (mean diameter of 0.000–0.100 mm) with SOC, AK, and pH. In contrast, fine sand and medium sand (mean diameter of 0.100–0.500 mm) showed significant negative correlations with these indicators. Our findings ascertain that the plantation of *S. vulgaris* requires 10 years to effectively act as a windbreak and contribute to sand fixation, and needs 16 years to improve soil physical and chemical properties. Importantly, these improvements were found to be highly beneficial for vegetation restoration in arid and semi-arid areas. This research can offer valuable insights for the protection and restoration of the vegetation ecosystem in the sandy lands in China.

Keywords: *Sabina vulgaris*; plantation age; soil physical and chemical properties; soil particle size; soil fertility; vegetation restoration; Mu Us Sandy Land

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1 Introduction

China's Mu Us Sandy Land is one of the country's four major sandy lands. Its ecological environment is fragile and has experienced the most serious desertification (Wang and Zhu, 2001; Zhao et al., 2016; Cui et al., 2019). Some good vegetation restoration measures (such as afforestation and grazing prohibition) have been implemented and have controlled the desertification process, driving some areas dominated by fixed and semi-fixed dunes, and even

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the reversal of desertification under favorable climate conditions (Yang et al., 2010; Liang and Yang, 2016; Xu et al., 2018; Cui et al., 2019; Li et al., 2021). In the process of vegetation restoration, the disadvantages of exotic introduced species are gradually revealed, mainly manifested as fast growth and higher water consumption accompanied with high mortality (Deng et al., 2016). An excellent native afforestation species, *Sabina vulgaris*, is widely noticed, which is a typical evergreen shrub that spreads clonally to form dense patches of natural vegetation and grows vigorously for hundreds of years in the Mu Us Sandy Land (He, 2000; He and Zhang, 2003; Li et al., 2012). Some studies showed that *S. vulgaris* species itself has the characteristics of drought resistance, cold resistance, and heat resistance, which can function as a windbreak and increase sand fixation (Song et al., 2003; Wei and Xin, 2003; He, 2007), playing an important role in the prevention and control of desertification. More research focused on the growth characteristics, adaptation strategies, and cultivation techniques of *S. vulgaris* (Zhao et al., 2013; Wang et al., 2015; Nan et al., 2020; Gao et al., 2023; Wen et al., 2023). However, few research was conducted to explore the process of improving soil physical and chemical properties by the plantation of *S. vulgaris*.

Soil physical and chemical properties, as the basic attributes and essential characteristics of soil, are also important indicators to determine soil fertility and quality and key ecological factors to control plant growth and development. In addition, the vegetation itself and the soil physical properties crucially affect vegetation restoration accompanied with the soil nutrient elements. In arid and semi-arid areas, the sparse or discontinuous vegetation, scarce water, and suboptimal soil fertility are interconnected through intricate feedback mechanisms and interactions (Wu et al., 2016; Li et al., 2018b; Zhang et al., 2018; Shi et al., 2020). Soil comprises a variety of particle sizes, with distinct particle size fractions offering varied contributions to the soil nutrient supply capacity (Wang et al., 2000; Deng and Shangguan, 2017; Zhang et al., 2018). Some studies have revealed that vegetation growth in the Tengger Desert, China corresponds with the shifts in soil physical properties, such as particle size distribution and structure (Duan et al., 2004; Li et al., 2007). Conversely, vegetation restoration in the Mu Us Sandy Land correlates with the increase in soil fine particle content, the improvement of soil structure, and the enhancement of soil carbon fixation (Chen and Duan, 2009; Yang et al., 2012; Zhang et al., 2016). Some other studies have indicated that artificial vegetation alters soil physical and chemical properties in the Mu Us Sandy Land, with notable improvement in physical properties while minimal changes in chemical properties (Guan et al., 2013; Yang et al., 2014). Consequently, variability persists regarding the improvement in soil chemical properties in desert landscapes.

Changes in soil physical properties often coincide with shifts in specific chemical attributes, facilitating biogeochemical cycles. However, desert conditions can lead to soil material and nutrient losses via wind erosion. The extent to how the plantation of *S. vulgaris* affects these soil properties and what is the level of dependency of soil chemical properties on physical ones during vegetation restoration process remains uncertain. Additionally, questions arise regarding the duration that the plantation of *S. vulgaris* requires to influence soil properties and concerning its efficacy as a windbreak for sand fixation. To address these queries, we assessed soil physical and chemical properties across four *S. vulgaris* plantation ages in the Mu Us Sandy Land, aiming to: (1) track changes in soil physical and chemical properties during the growth of *S. vulgaris* plantations; (2) understand the response of soil chemical properties to physical ones; and (3) determine the influence of the plantation of *S. vulgaris* on soil physical and chemical properties and its ecological effect. By substituting time with space, this study delineated the ecological effect of the plantation of *S. vulgaris* on soil properties and local environment, offering insights into the potential of desert vegetation restoration to improve soil quality in broader ecosystems.

2 Materials and methods

2.1 Study area

This study was conducted in the Mu Us Sandy Land in Shaanxi Province, China, spanning an area

of 766.6 km^2 (38°12′–39°27′N, 109°39′–110°54′E). Positioned on the southeastern edge of the Mu Us Sandy Land, the study area has an average elevation of 1200 m. We selected semi-fixed sand dunes as the experimental plots. The region experiences sunlight averaging between 2593 and 2914 h annually. Winter temperatures fluctuate between –7.8°C and 4.1°C, while summer temperatures surpass 20.0°C, culminating in an annual average temperature of 9.6°C. From 2001 to 2018, the average annual precipitation was 465.4 mm, with approximately 70.2% occurring between June and August. Harsh conditions characterized by drought, potent winds, and regular sandstorms prevail during winter and spring (Kottek et al., 2006). The soil, comprising less than 0.35% of silt and approximately 99.65% of sand, aligns with the Arenosol classification based on the World Reference Base for Soil Resources (FAO, 2015). Given its loose and infertile nature, the soil is highly prone to wind erosion. Presently, the region is witnessing expansive stabilization through vegetation, transitioning most sandy soils from a mobile state to semi-fixed or completely fixed states. Prior to afforestation, the experimental plots were predominantly featured with mobile dunes and quicksand. The dominant soil in these plots ranged from fine to medium sands (Yang et al., 2018).

2.2 Experimental design and soil sampling

The experiment involved four age treatments of *S. vulgaris* plantations: 4, 7, 10, and 16 years. These treatments were organized in a completely randomized block design, comprising three 10 m×10 m plots for each treatment, totaling 12 plots. To ensure uniformity, we assigned all plots on a south-facing windward slope with inclinations between 5° and 35°. Plantations were spaced at 1 m×1 m intervals, resulting in a density of 10,000 stems/hm^2. Each plant, before being transplanted, had a ground-level stem diameter of approximately 10 cm. Each two plots were spaced at least 50 m apart.

For each plantation, one soil sample was taken from each of its three plots. These three soil samples were then combined to form a single composite sample for soil analysis. Sampling was conducted in November 2019 across five soil depth layers: 0–20, 20–40, 40–60, 60–80, and 80–100 cm. This depth range was chosen because over 90% of the root mass is located within the top 100 cm of the soil (He, 2000).

We measured soil bulk density (g/cm^3) using cutting-ring method and particle density (g/cm^3) with pycnometer methods (ISSCAS, 1978). Soil particle size distribution was assessed using a laser diffraction analyzer (Mastersizer-2000, Malvern Panalytical Ltd., Worcestershire, United Kingdom). We determined soil organic carbon (SOC; g/kg) using potassium dichromate volumetric method with external heating (Nelson and Sommers, 1982), total nitrogen (TN; mg/kg) based on the semi-micro Kjeldahl procedure (UDK 140 Automatic Steam Distilling Unit, Automatic Titroline 96, La ville Udine, Italy) (ISSCAS, 1978), available nitrogen (AN; mg/kg) using alkali hydrolysis (ISSCAS, 1978), available phosphorus (AP; mg/kg) according to the Olsen method (ISSCAS, 1978), available potassium (AK; mg/kg) based on the flame photometry after extraction with 1 M NH_4OAc, cation-exchange capacity (CEC; cmol/kg) using 1 mol/L NaOAC, salinity (g/kg) using a conductivity-based soil salinity tachometer (DDSJ-308, Shanghai Yidian Scientific Instrument Co., Ltd., Shanghai, China), and pH using the potentiometric method.

2.3 Data analysis of soil physical and chemical properties

Soil porosity (SP; %) was calculated as follows:

$$\mathrm{SP}=\left(1-\frac{\rho_0}{\rho_b}\right)\times 100\% , \tag{1}$$

where ρ_0 is the soil bulk density (g/cm^3) and ρ_b is the soil particle density (g/cm^3).

In soil particle size analysis, particle size was measured using phi (φ) unit (φ= $-\log_2 d$, where d is the particle size (mm)). The particle size distribution was expressed by four parameters, i.e., mean particle size (Mz; φ), sorting (σ; φ), skewness (S_K), and kurtosis (K_G). We calculated these parameters based on the cumulative curves and formulas proposed by Folk and Ward (1957):

$$M_z = \frac{1}{3}(\varphi_{16} + \varphi_{50} + \varphi_{84}), \tag{2}$$

$$\sigma = \frac{1}{4}(\varphi_{84} - \varphi_{16}) + \frac{1}{6.6}(\varphi_{95} - \varphi_5), \tag{3}$$

$$S_K = \frac{\varphi_{16} + \varphi_{84} - 2\varphi_{50}}{2(\varphi_{84} - \varphi_{16})} + \frac{\varphi_5 + \varphi_{95} - 2\varphi_{50}}{2(\varphi_{95} - \varphi_5)}, \tag{4}$$

$$K_G = \frac{\varphi_{95} - \varphi_5}{2.44(\varphi_{75} - \varphi_{25})}, \tag{5}$$

where φ represents the logarithmic boundary transformation for particle size grade (phi). The numbers that follow φ represent the percentiles of the particle size content in the cumulative curves. Table 1 shows the Udden-Wentworth particle size classification (Udden, 1914; Wentworth, 1922) and the grading standard of particle size parameters (Folk and Ward, 1957). The particle size parameters can be used to determine sediment material deposition environments.

Table 1 Particle size classification and the grading standard of particle size parameters

Mean particle size		Sorting		Skewness		Kurtosis	
Range (φ)	Definition	Range (φ)	Definition	Range	Definition	Range	Definition
> 9.00	Clay	<0.35	Very well sorted	–1.00– –0.30	Very negative skewed	<0.67	Very platykurtic
4.00–9.00	Silt sand	0.35–0.50	Well sorted	–0.30– –0.10	Negative skewed	0.67–0.90	Platykurtic
3.00–4.00	Very fine sand	0.50–1.00	Moderately sorted	–0.10–0.10	Nearly symmetrical	0.90–1.11	Mesokurtic
2.00–3.00	Fine sand	1.00–2.00	Poorly sorted	0.10–0.30	Positive skewed	1.11–1.50	Leptokurtic
1.00–2.00	Medium sand	2.00–4.00	Very poorly sorted	0.30–1.00	Very positive skewed	1.50–3.00	Very leptokurtic
0.00–1.00	Coarse sand	>4.00	Extremely poorly sorted			>3.00	Extremely leptokurtic
–1.00–0.00	Very coarse sand						

Coefficient of variation (CV; %) was calculated as follows:

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mu} \times 100\%, \tag{6}$$

where SD is the standard deviation and μ is the mean value for each soil chemical indicator.

2.4 Statistical analysis

A one-way analysis of variance (ANOVA) was employed to compare soil particle size distribution and soil chemical properties (including the SOC, TN, AN, AP, AK, CEC, salinity, and pH) across the four plantation ages. If ANOVA analysis yielded significant results, a *t*-test was applied to discern significant differences between age pairs. Significance was set at the $P<0.05$ level. Pearson's correlation coefficient (r) values were calculated to ascertain the relationships between soil chemical properties and soil particle size distribution. The principal component analysis (PCA) was used to determine the contribution of each soil chemical indicator to comprehensive soil fertility using SPSS 26.0 (SPSS Inc., Chicago, USA). Graphs were produced using SigmaPlot 12.5 (SYSTAT Inc., San Jose, USA).

3 Results

3.1 Characteristics of the variations in soil physical properties

In the study area, soil bulk density generally decreased with increasing plantation age across all depths (Fig. 1). Nevertheless, variations in soil bulk density among the four plantation ages were

minimal. The average soil bulk density up to a depth of 100 cm was 1.63, 1.63, 1.59, and 1.58 g/cm^3 for the 4-, 7-, 10-, and 16-year-old plantations, respectively. Simultaneously, the mean soil porosity up to a depth of 100 cm showed a slight increase: 38.88%, 38.46%, 40.18%, and 40.58% for the 4-, 7-, 10-, and 16-year-old plantations, respectively. Notably, no significant differences in soil porosity were observed across the four plantation ages.

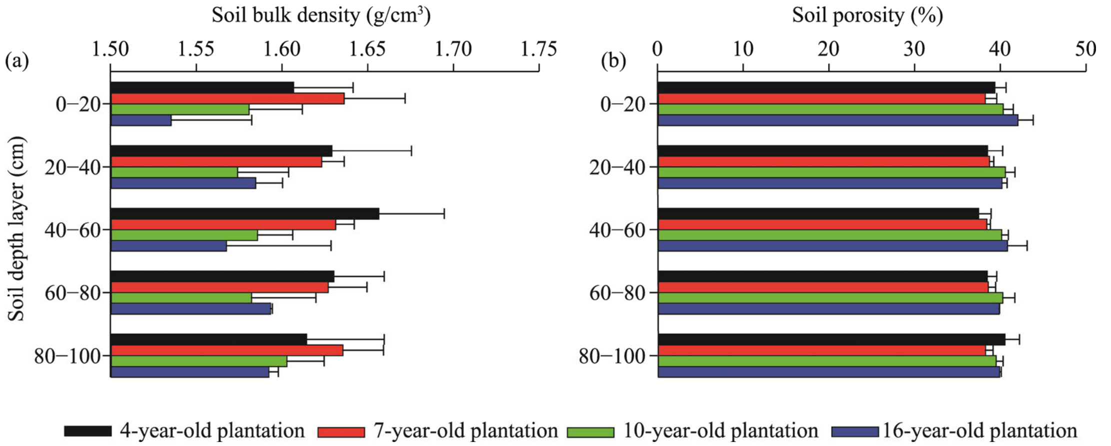

Fig. 1 Variations in soil bulk density (a) and soil porosity (b) at different soil depth layers in the 4-, 7-, 10-, and 16-year-old *S. vulgaris* plantations. Bars mean standard errors (n=3).

The soil particle size distribution revealed that fine and medium sands were predominant, constituting between 93.45% and 99.76% of the volume (Table 2). The medium sand content peaked at over 45.58% (±6.60%), while the clay content was minimal, under 0.21% (±0.07%). With increasing plantation age, soil particle size distribution exhibited increases in silt, very fine sand, and coarse sand contents. Moreover, in the 16-year-old plantation, the medium sand made up 46.21% (±0.45%) of the volume across all soil depth layers, which was notably lower than the medium sand content in the 4-, 7-, and 10-year-old plantations (49.63% (±1.64%), 49.17% (±1.29%), and 52.90% (±0.84%), respectively) (Table 2; Fig. 2a).

The frequency distribution curves indicated that, in both the 0–100 cm soil profile and the 0–20 cm soil depth layer, soil particle size exhibited a single peak for the 4-, 7- and 10-year-old plantations, but displayed dual peaks for the 16-year-old plantation (Fig. 2b1–b2). These peaks primarily ranged between 0.200 and 0.400 mm. The peak soil particle size of the 4-year-old plantation was 0.280 mm, with a maximum probability percent of 11.43%. For the 16-year-old plantation, the peak soil particle size was 0.400 mm, with a minimum probability percent of 8.52%. The cumulative probability curves highlighted that steeper curves were correlated with more intense sand activity (Dong et al., 2013). For soil particle sizes under 0.100 mm, the cumulative probability curves in the 4-, 7-, and 10-year-old plantations were more gradual, suggesting weaker sand activity (Fig. 2c1–c2). Conversely, the curve for the 16-year-old plantation was steeper, indicating intensified sand activity. Yet, for soil particle sizes exceeding 0.190 mm, the curves for the 4- and 7-year-old plantations became steeper, whereas those for the 10- and 16-year-old plantations flattened, implying a reduction in sand activity.

Subsequent analysis of soil particle size parameters showed that the mean particle sizes in the 16- and 10-year-old plantations were 1.66 and 1.73 φ, respectively, and were notably lower than the values in the 4- and 7-year-old plantations (1.95 and 1.87 φ, respectively) (P<0.05; Fig. 3). Sorting of the soil in the oldest plantation (16-year-old) was significantly higher (poorly sorted) compared to the younger plantations (moderately sorted), regardless of depths. Among the three younger plantations (4-, 7-, and 10-year-old plantations), sorting of the soil remained relatively consistent across different depth layers. Soil samples in all plantations exhibited negative skewness values, with skewness in the 16-year-old plantation being more pronounced (very negatively skewed)

Table 2 Soil particle size distribution in different soil depth layers in the 4-, 7-, 10-, and 16-year-old *S. vulgaris* plantations

Plantation age	Soil depth layer (cm)	Soil particle size distribution (%)						
		Clay (0.000–0.002 mm)	Silt (0.002–0.050 mm)	Very fine sand (0.050–0.100 mm)	Fine sand (0.100–0.250 mm)	Medium sand (0.250–0.500 mm)	Coarse sand (0.500–1.000 mm)	Very coarse sand (1.000–2.000 mm)
4-year-old	0–20	0.00±0.00	1.35±0.83	0.17±0.13	46.79±7.23	48.28±3.97	3.41±3.11	0.00±0.00
	20–40	0.00±0.00	0.59±0.15	0.09±0.30	48.61±1.52	48.31±1.71	2.39±0.38	0.00±0.00
	40–60	0.00±0.00	0.53±0.05	0.03±0.22	44.02±3.33	51.91±2.94	3.51±0.91	0.00±0.00
	60–80	0.00±0.00	0.58±0.36	0.09±0.28	44.71±7.88	50.80±4.98	3.81±3.21	0.00±0.00
	80–100	0.00±0.00	0.49±0.20	0.07±0.17	47.56±1.96	48.83±1.27	3.05±0.64	0.00±0.00
	Mean	0.00±0.00	0.71±0.36^{bc}	0.09±0.05^{c}	46.34±1.93^{a}	49.63±1.64^{b}	3.23±0.54^{c}	0.00±0.00
7-year-old	0–20	0.00±0.00	0.52±0.47	0.24±0.18	44.12±9.08	50.13±5.17	4.75±3.60	0.00±0.00
	20–40	0.00±0.00	0.29±0.50	0.44±0.20	50.67±1.56	48.40±1.51	2.38±0.23	0.00±0.00
	40–60	0.00±0.00	0.24±0.41	0.26±0.21	45.66±6.48	49.43±4.43	4.18±2.29	0.00±0.00
	60–80	0.00±0.00	0.00±0.00	0.42±0.17	46.97±7.69	47.36±4.27	4.21±3.39	0.00±0.00
	80–100	0.00±0.00	0.35±0.41	0.27±0.20	42.51±6.24	50.53±3.48	5.43±2.32	0.00±0.00
	Mean	0.00±0.00	0.28±0.19^{c}	0.34±0.10^{bc}	45.98±3.11^{a}	49.17±1.29^{b}	4.19±1.13^{c}	0.00±0.00
10-year-old	0–20	0.00±0.00	0.75±0.52	0.36±0.36	26.42±5.31	52.53±2.08	20.07±6.15	0.00±0.00
	20–40	0.00±0.00	0.46±0.06	0.40±0.37	29.75±3.77	52.50±5.46	15.48±3.28	0.00±0.00
	40–60	0.00±0.00	0.98±0.04	0.31±0.25	32.96±2.35	51.96±3.43	14.43±4.93	0.00±0.00
	60–80	0.00±0.00	1.05±0.53	0.78±1.32	35.32±5.98	53.45±9.52	10.60±2.42	0.00±0.00
	80–100	0.00±0.00	1.27±0.65	0.34±0.46	27.33±4.56	54.06±2.52	16.93±4.81	0.00±0.00
	Mean	0.00±0.00	0.90±0.31^{b}	0.44±0.19^{b}	30.36±3.74^{b}	52.90±0.84^{a}	15.40±3.47^{b}	0.00±0.00
16-year-old	0–20	0.16±0.14	6.39±1.83	3.83±0.76	23.59±4.35	45.93±1.61	19.94±5.49	0.06±0.11
	20–40	0.17±0.19	5.71±2.82	3.68±1.88	23.85±5.37	46.66±3.46	19.83±6.50	0.00±0.00
	40–60	0.18±0.39	5.41±6.49	4.69±4.05	19.39±5.90	45.58±6.60	24.51±10.07	0.14±0.25
	60–80	0.19±0.14	5.04±1.41	4.42±0.68	22.36±1.85	46.56±2.01	21.33±1.06	0.00±0.00
	80–100	0.21±0.07	5.01±0.74	4.41±0.72	22.94±1.69	46.34±0.90	20.99±1.23	0.00±0.00
	Mean	0.18±0.02	5.51±0.57^{a}	4.21±0.43^{a}	22.43±1.79^{c}	46.21±0.45^{c}	21.32±0.19^{a}	0.05±0.06

Note: Values are mean±standard deviation. Different lowercase letters within the same row indicate significant differences among different particle size fractions at the P<0.05 level.

than the values in the 4-, 7-, and 10-year-old plantations (nearly symmetrical). Kurtosis reflects the sand sediment formation environment. Extreme high or low kurtosis values indicate that the sediment is a mixture of different materials (such as those deposited in a high- or low-energy environment) (Folk and Ward, 1957). The kurtosis value of the soil in the 16-year-old plantation was significantly higher (leptokurtic) than those in the younger plantations (mesokurtic). In the 4-, 7-, and 10-year-old plantations, the less soil fine particle accumulation occurred with stronger wind erosion. Conversely, in the 16-year-old plantation, with the weakening of wind and the anti-dust effect of vegetation, the captured fine particles increased.

3.2 Characteristics of the variations in soil chemical properties

Figure 4 illustrates the variations in soil chemical properties across all soil depth layers in the 4-, 7-, 10-, and 16-year-old *S. vulgaris* plantations, and their mean values are presented in Table 3. Across the entire soil profile (0–100 cm), the mean SOC content ranged from 1.20 to 4.69 g/kg (Fig. 4a). When considering all the five soil depth layers, the mean SOC content followed this sequence: 16-year-old plantation (3.80 g/kg)>4-year-old plantation (1.95 g/kg)>10-year-old plantation (1.81 g/kg)>7-year-old plantation (1.78 g/kg). Notably, the SOC content in the oldest

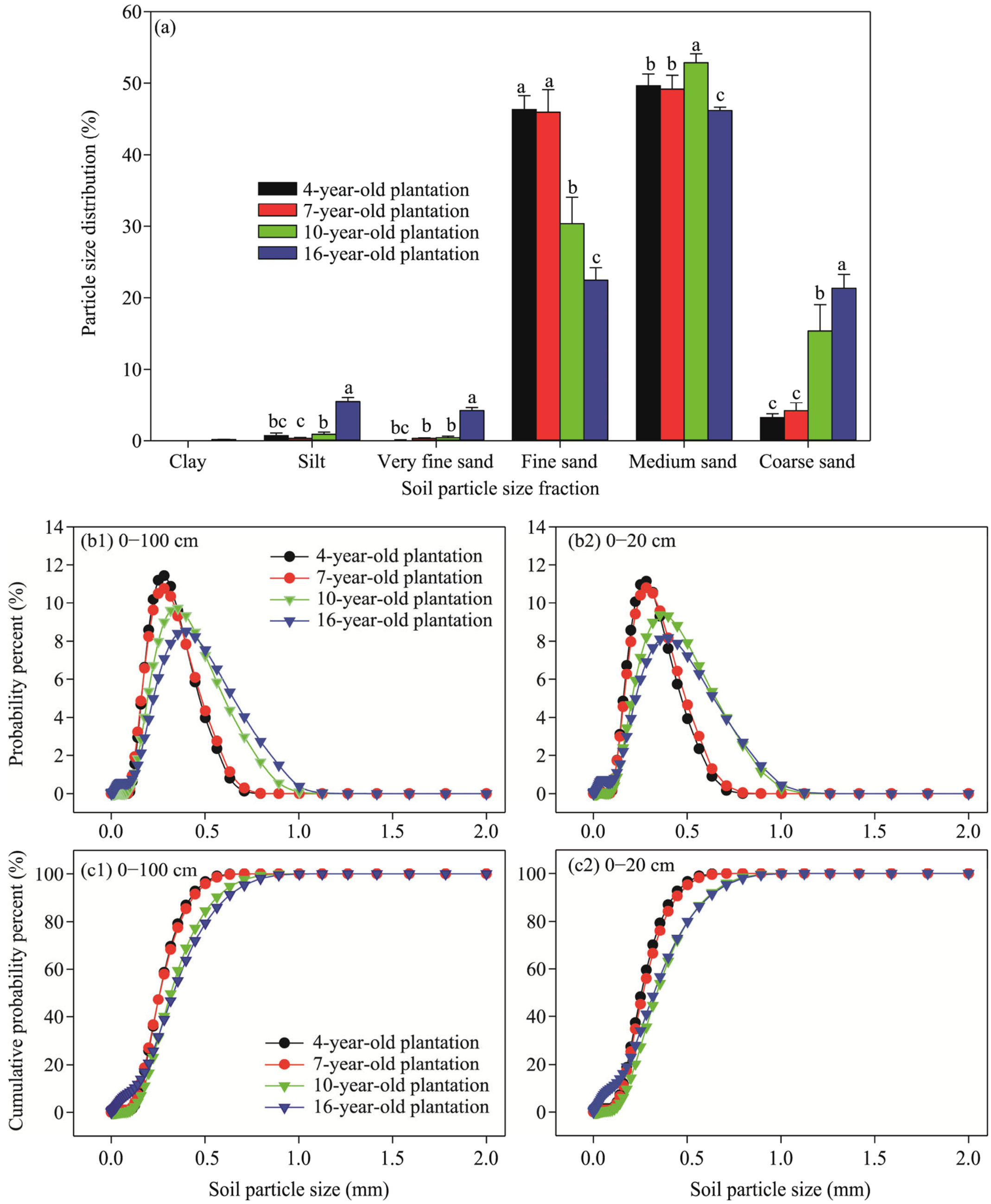

Fig. 2 Soil particle size distribution (a), frequency distribution curves of soil particle size in the 0–100 cm soil profile (b1) and 0–20 cm soil depth layer (b2), and cumulative probability curves of soil particle size in the 0–100 cm soil profile (c1) and 0–20 cm soil depth layer (c2) in the 4-, 7-, 10-, and 16-year-old *S. vulgaris* plantations. Different lowercase letters within the same particle size fraction indicate significant differences among the four plantation ages at the $P<0.05$ level. Bars mean standard errors.

plantation (16-year-old) exhibited a significantly higher value than those in the younger plantations (4-, 7-, and 10-year-old plantations). While the SOC content showed a decreasing trend from 7-year-old plantation to 10-year-old plantation in the top 40 cm soil layer, it generally increased with plantation age. The mean TN content fluctuated between 41.27 and 68.26 mg/kg across the whole soil profile (Fig. 4b). When considering all the five soil depth layers, the mean TN content followed the order of 4-year-old plantation (55.76 mg/kg)>16-year-old plantation

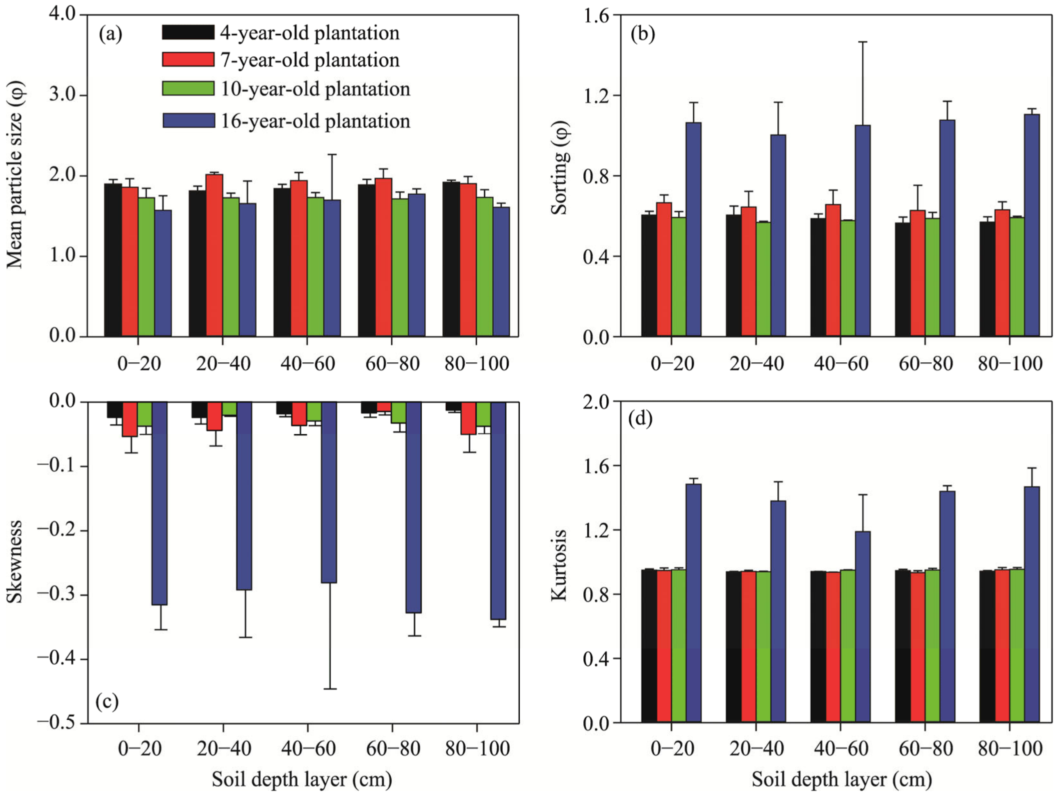

Fig. 3 Variations in the soil particle size parameters across all soil depth layers in the 4-, 7-, 10-, and 16-year-old *S. vulgaris* plantations. (a), mean particle size; (b), sorting; (c), skewness; (d), kurtosis. Bars mean standard errors.

(54.78 mg/kg)>7-year-old plantation (53.36 mg/kg)>10-year-old plantation (53.22 mg/kg); however, these values showed no significant variations across the four plantation ages.

As depicted in Figure 4c, the mean AN content across all the five soil depth layers followed this sequence: 16-year-old plantation (22.20 mg/kg)>7-year-old plantation (19.68 mg/kg)>4-year-old plantation (18.67 mg/kg)>10-year-old plantation (14.72 mg/kg). Significantly, the AN content in the 16-year-old plantation surpassed those in the 4- and 10-year-old plantations. The sequence for the mean AP content, as shown in Figure 4d, was as follows: 4-year-old plantation (1.62 mg/kg)>16-year-old plantation (0.92 mg/kg)>7-year-old plantation (0.85 mg/kg)>10-year-old plantation (0.76 mg/kg). The mean AP content in the 4-year-old plantation significantly exceeded those in the other three plantations. For the AK content (Fig. 4e), the 16-year-old plantation stood out with significantly higher values (mean of 50.46 mg/kg) than the younger plantations (<27.00 mg/kg), which remained largely comparable.

The soil in the study area was non-saline and mildly alkaline (Fig. 4f–h), which is suitable for plant growth. Neither the salinity, CEC, nor pH showed significant variations based on soil depth layers or plantation ages. As shown in Table 3, salinity was between 0.10 and 0.20 g/kg, CEC fluctuated from 12.79 to 13.18 cmol/kg, and pH ranged from 7.38 to 7.60. Our findings suggest that the plantation of *S. vulgaris* didn't significantly affect the CEC or salinity in the soil.

3.3 Relationships between soil chemical properties and particle size fraction

Our analysis revealed marked differences in the interactions between soil chemical properties and particle size fraction (Table 4). SOC, AK, and pH were positively correlated with the clay, silt, very fine sand, and coarse sand (r>0.47; P<0.05). Among these, the strongest correlation was observed in clay (correlation coefficients of 0.84 for SOC, 0.88 for AK, 0.60 for pH, and 0.49 for salinity), succeeded by silt (correlation coefficients of 0.84 for SOC, 0.92 for AK, and 0.48 for pH),

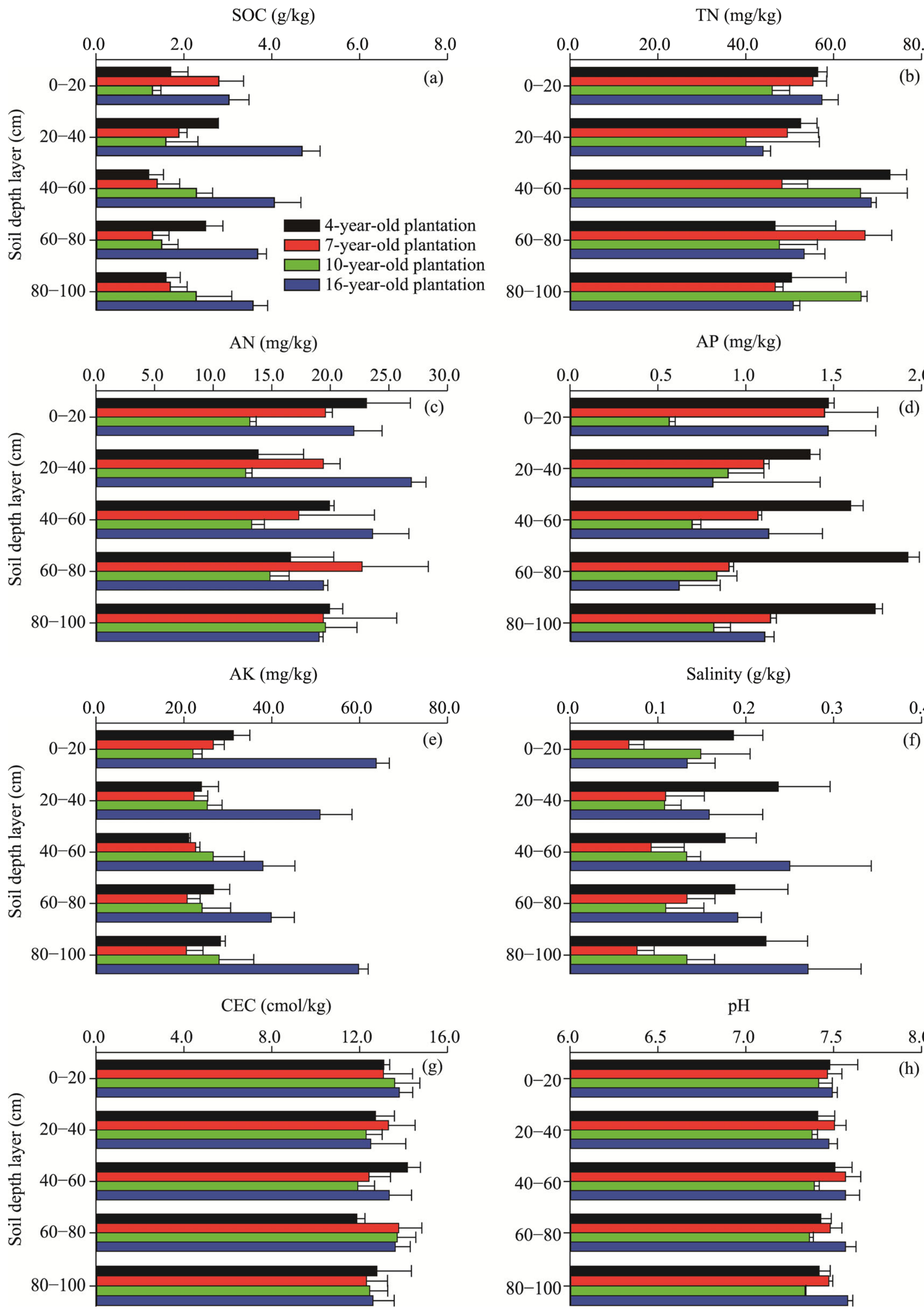

Fig. 4 Variations in the soil chemical properties across all soil depth layers in the 4-, 7-, 10-, and 16-year-old *S. vulgaris* plantations. (a), soil organic carbon (SOC); (b), total nitrogen (TN); (c), available nitrogen (AN); (d), available phosphorus (AP); (e), available potassium (AK); (f), salinity; (g), cation-exchange capacity (CEC); (h), pH. Bars mean standard errors.

Table 3 Statistical characteristics of soil chemical properties in the 0–100 cm soil profile

Property	4-year-old plantation			7-year-old plantation			10-year-old plantation			16-year-old plantation		
	μ	SD	CV	μ	SD	CV	μ	SD	CV	μ	SD	CV
SOC (g/kg)	1.95^{b}	0.66	33.62	1.81^{b}	0.60	33.12	1.78^{b}	0.46	26.00	3.80^{a}	0.62	16.80
TN (mg/kg)	55.76^{a}	10.17	18.24	53.36^{a}	8.36	15.66	53.22^{a}	12.17	22.88	54.78^{a}	9.10	16.61
AN (mg/kg)	18.67^{bc}	3.55	19.01	19.68^{ab}	1.93	9.83	14.72^{cd}	2.83	19.22	22.20^{a}	4.01	18.93
AP (mg/kg)	1.62^{a}	0.22	13.56	0.85^{bc}	0.26	31.32	0.76^{bc}	0.13	17.43	0.92^{b}	0.53	57.96
AK (mg/kg)	26.27^{b}	3.91	14.89	22.59^{b}	2.46	10.91	24.96^{b}	2.40	9.61	50.46^{a}	11.53	22.84
Salinity (g/kg)	0.20^{a}	0.03	13.02	0.10^{bc}	0.03	27.63	0.13^{b}	0.02	13.99	0.20^{a}	0.06	29.25
CEC (cmol/kg)	12.93^{a}	0.83	6.42	12.98^{a}	0.61	4.74	12.79^{a}	0.81	6.31	13.18^{a}	0.59	4.49
pH	7.45^{bc}	0.04	0.57	7.50^{ab}	0.04	0.56	7.38^{c}	0.03	0.39	7.54^{a}	0.05	0.66
C/N ratio	35.00			33.90			33.40			69.40		

Note: μ, mean value; SD, standard deviation; CV, coefficient of variation; SOC, soil organic carbon; TN, total nitrogen; AN, available nitrogen; AP, available phosphorus; AK, available potassium; CEC, cation-exchange capacity; C/N ratio, the ratio of soil organic carbon to total nitrogen. Different lowercase letters within the same row indicate significant differences among the four plantation ages at the $P<0.05$ level.

Table 4 Correlation coefficients between soil chemical properties and particle size fraction

	Clay	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand
SOC	0.842^{**}	0.837^{**}	0.825^{**}	-0.664^{**}	-0.567^{**}	0.667^{**}	0.434
AK	0.878^{**}	0.917^{**}	0.845^{**}	-0.509^{**}	-0.676^{**}	0.591^{**}	0.357
pH	0.599^{**}	0.476^{*}	0.606^{**}	-0.742^{*}	-0.541^{*}	0.732^{**}	0.349
Salinity	0.485^{*}	0.419	0.438	–0.020	–0.031	0.009	0.313
TN	0.027	0.068	0.064	–0.062	0.112	0.008	0.370
AN	–0.286	–0.196	–0.308	0.409	–0.224	–0.406	–0.115
AP	0.239	0.309	–0.259	–0.354	–0.153	0.383	0.364
CEC	0.162	0.193	0.204	–0.180	–0.041	–0.155	0.240

Note: *, $P<0.05$ level; **, $P<0.01$ level.

very fine sand (correlation coefficients of 0.83 for SOC, 0.85 for AK, and 0.61 for pH), and coarse sand (correlation coefficients of 0.67 for SOC, 0.59 for AK, and 0.73 for pH). Conversely, SOC, AK, and pH were significantly negatively correlated with fine sand and medium sand ($r< -0.50$; $P<0.05$). Among these, the most pronounced negative correlation was recorded in fine sand (correlation coefficients of –0.66 for SOC, –0.51 for AK, and –0.74 for pH), trailed by medium sand (correlation coefficients of –0.57 for SOC, –0.68 for AK, and –0.54 for pH).

4 Discussion

4.1 Effect of the plantation of *S. vulgaris* on soil physical and chemical properties

During the 4–16 years after planting, the *S. vulgaris* shrubs exhibited robust growth, coinciding with the increases in soil bulk density and soil porosity, especially on a 10-year scale. Consequently, the plantation of *S. vulgaris* may ameliorate soil conditions, aligning with earlier findings (Guan et al., 2013; Wei and Wei, 2017). Previous research has indicated the pivotal role of soil clay content in influencing soil biogeochemical cycles and determining soil nutrient contents (Deng and Shangguan, 2017). Our observations highlight that the 16-year-old *S. vulgaris* plantation had the maximum silt content (mean of 5.51%), a magnitude significantly higher than the other plantation age groups (Table 2). No clay was detected in the plantations younger than 16 years old, while moderate levels (lower than 0.18%) were identified at this age. As the *S. vulgaris*

plantation age increased, the mean soil particle size became smaller, with a notable shift towards finer particles after 16 years of planting, paralleling prior research outcomes (Su et al., 2004). Improved sedimentary conditions, associated with vegetation mitigating the dispersal of sand and dust, resulted in the capture of more fine particles (Cui et al., 2019). Although our study spanned a mere 16 years, the soil physical properties, including soil bulk density, particle size distribution, and silt and clay contents, underwent marked transformations.

Alterations in soil physical properties were cooperated with shifts in soil chemical properties, thus advancing soil biogeochemical cycles and influencing the distribution of soil nutrient elements. With increasing plantation age, the SOC was decreased slightly first and then increased, which agrees with previous studies (He and Wang, 2003; Sang et al., 2017; Wei and Wei, 2017). After 16 years of afforestation, the SOC content in the study area oscillated between 3.03 and 4.69 g/kg, lower than the values (from 4.84 to 8.64 g/kg) in the analogous fragile Horqin Sandy Land, China (Li et al., 2018c). The possible reason could be the suboptimal water content and sluggish plant growth typical of arid zones, such as our study area. This resulted in minimal litter sedimentation and scarce release of root exudates into the soil when vegetation cover remains sparse (Tang et al., 2019). Hence, the TN content remained extremely low (<55.76 mg/kg) and exhibited negligible variation with plantation age, which can be attributable to the minimal nitrogen fixation in the sandy land. It is well known that afforestation can capture carbon and nitrogen, thereby increasing the available nutrients in the soil and enabling plants to grow in the nutrient-deficient land (Xu et al., 2010; Qin et al., 2013). Our findings mirrored this, showcasing a slight reduction in the AN and AP contents from 7 to 10 years of planting, succeeded by a marked increase, echoing findings from the southeastern margin of the Mu Us Sandy Land (Zhang et al., 2013; Wei and Wei, 2017; Shi et al., 2020). As the shrub age increases, a pronounced soil C/N ratio (>25:1) up to a soil depth of 100 cm initially declined before ascending (Table 3), suggesting microbial competition with plants for inorganic nitrogen, thereby modulating plant growth dynamics (Elser et al., 2007; Tang et al., 2019). This infers that, alongside water, a dearth of nitrogen has emerged as an additional growth-limiting factor in the sandy land.

No discernible trends were evident regarding soil nutrient contents in relation to soil depth layers. The inherent characteristics of aeolian sandy soil, characterized by subpar water and nutrient retention capacities, as noted in other sandy lands (e.g., Horqin Sandy Land), could be the reason (Li et al., 2018c). We also observed that the SOC content initially climbed with soil depth (peaking in the depth layer of 40–60 cm), while other chemical properties didn't reflect a similar trend. It appears that soil nutrients predominantly avoid surface accumulation, which hinders the accumulation of carbon (He and Zhang, 2003; Yang et al., 2014). Such disparities might arise from insufficient accumulation of dead branches and leaves in plantations and their slow decomposition, a consequence of the warm but relatively dry conditions of sandy land that prevail in our study area (Nan et al., 2020).

4.2 Effect of the plantation of *S. vulgaris* on soil fertility

Effect of soil resource changes on plants is a very long-term and effective experimentation. Our results revealed relatively low contents of soil nutrient elements (AN, AP, and AK) and weakly alkaline soil in the *S. vulgaris* plantations. In the process of desertification reversal, the response of soil properties to plant changes was very long-term. To discern any correlation between soil fertility and plantation age, we explored the soil chemical indicators (SOC, TN, AN, AP, AK, CEC, salinity, and pH) using the PCA to unveil soil fertility. The leading three principal components, focusing on SOC, AK, and pH, explained 70.80% of the total variance, thus prominently representing soil fertility (Table 5). The comprehensive soil fertility scores were –0.14, –0.43, –0.42, and 1.00 for the 4-, 7-, 10-, and 16-year-old plantations in sequence. Consequently, the soil fertility declined from 4 to 7 years after planting and subsequently ascended from 10 to 16 years after planting. A plausible rationale is the consumption of soil nutrients by swiftly growing plants, culminating in a decline in soil fertility. Beyond 10 years of planting, soil nutrients progressively accumulated, a phenomenon attributed to litter deposition

and root exudate contributions (Deng and Shangguan, 2017; Li et al., 2018c).

Soil is a mixture of particles spanning varied size fractions, and the particle size distribution can affect soil's nutrient supply capacity. This suggests a potential correlation between soil particle size distribution and soil nutrient elements (Li et al., 2017; Sang et al., 2017). Extensive research attests to the precision of the laser diffraction technique in delineating soil particle size distribution (Li et al., 2018a; Duan et al., 2020). We, therefore, evaluated the interplay between soil particle size distribution and related soil chemical indicators. Analyses revealed that SOC, AK, and pH exhibited marked positive correlations with clay to very fine sand (0.000–0.100 mm) and pronounced negative relationships with fine sand to medium sand (0.100–0.500 mm), aligning with prior findings (Tang et al., 2009; Zhang et al., 2016). Thus, as the coarse sand content increased, the soil chemical indicators (SOC, AK, and pH) decreased significantly ($P<0.05$), which was consistent with the results of Li et al. (2017).

Table 5 Results of the principal component analysis (PCA) to determine the contributions of soil chemical properties to soil fertility

Principal component (PC)	Total variance explained	Proportion of the total variance explained (%)	Cumulative proportion (%)
PC1	2.433	30.407	30.407
PC2	1.834	22.930	53.337
PC3	1.397	17.464	70.800
PC4	0.912	11.402	82.203
PC5	0.572	7.150	89.352
PC6	0.481	6.016	95.368
PC7	0.200	2.506	97.874
PC8	0.170	2.126	100.000

Note: There was a strong correlation among the soil chemical indicators (Bartlett's test value=45.420; $P<0.001$), but the information overlap between the indicators was low based on the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (KMO=0.605).

4.3 Ecological effect of the plantation of *S. vulgaris*

During the process of *S. vulgaris* growth, soil structure will continuously improve, the persistent strong winds are easy to erode fine particles in the surface soil layer, resulting in the loss of nutrients during the process of sand and wind erosion. However, alterations in soil physical properties coincided with changes in soil nutrients, as observed after 16 years of planting *S. vulgaris* in the Mu Us Sandy Land. We noted that compared with the 4-year-old plantation, the fine particle content (0.000–0.100 mm) in the 16-year-old plantation increased by 11.18 times (Table 2), and the SOC, AN, AK, and C/N ratio significantly increased by 94.87%, 18.90%, 92.08%, and 98.29%, respectively, while the TN and AP diminished by 1.76% and 43.21%, respectively (Table 3). These changes in soil properties accelerated the transformation from the inorganic soil surface crusts in the initial plantation stages to the biological surface crusts, accompanied by soil nutrient accumulation after 10 years of planting (Chen et al., 2016). In the 16-year-old *S. vulgaris* plantation, the presence of a 4.35-mm thick moss-algae biological crust and over 32.5% of vegetation coverage (observed in the field) indicated that the growth of *S. vulgaris* may contribute to the accumulation of fine particles and a subsequent reduction of mean particle size in the soil (Ning et al., 2013). This result confirmed that the plantation of *S. vulgaris* with the age of 16-year-old had caused a fundamental change in soil structure. Nonetheless, between 4 and 10 years of planting, soil structure experienced minimal alterations, attributable to limited particle accumulation and prevalent wind erosion (Cui et al., 2019). Conversely, the increased trapping of fine particles and an enhanced sedimentary environment highlighted the significant role of *S. vulgaris* plantation in windbreak and sand fixation (Zhang et al., 2018; Pang et al., 2022). Overall, the plantation of *S. vulgaris* requires 10 years to effectively act as a windbreak and contribute to sand fixation, and needs 16 years to improve soil physical and chemical properties.

Over the past two decades, a combination of increased precipitation and temperature in the Mu Us Sandy Land has fostered a conducive environment for plant growth (Li et al., 2021; Zhu et al., 2022). Although our findings elucidated the potential of the plantation of *S. vulgaris* in vegetation restoration, it is imperative to consider the concurrent climatic amelioration. Throughout our study, elevated precipitation may notably bolster the growth of *S. vulgaris*, potentially improving soil conditions. Future research should delve into the ramifications of climate change on these dynamics.

5 Conclusions

The *S. vulgaris* plantations in the Mu Us Sandy Land, specifically those aged 4, 7, and 10 years, exhibited a relatively uniform soil particle size distribution, with little accumulation of fine particles (0.000–0.100 mm). In comparison to the 4-year-old plantation, the 16-year-old plantation showed an 11.18-fold increase in the content of fine particles, and significant enhancements in the SOC, AN, AK, and C/N ratio by 94.87%, 18.90%, 92.08%, and 98.29%, respectively. Conversely, the TN and AP diminished by 1.76% and 43.21%, respectively. These observations underscore the capability of mature plantations to trap windborne fine particles, resulting in a more refined mean particle size distribution and improved soil chemical properties. Initially, soil chemical indicators, such as the SOC, AN, AP, pH, salinity, and C/N ratio, experienced a slight downturn from 4 to 10 years of planting, followed by a marked increase from 10 to 16 years of planting. Post a decade of cultivation, *S. vulgaris* has notably ameliorated soil physical and chemical properties, serving as an effective windbreak and agent of sand fixation. This transformation became apparent after 16 years of planting, highlighting the plantation's substantial contribution to soil quality and ecological restoration. These findings provide a scientific basis for optimizing desertification prevention and control initiatives in arid and semi-arid areas.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

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